Measuring $V_{ub}$ From Exclusive Semileptonic Decays

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The Cabibbo-Kobayashi-Maskawa Matrix

- This matrix describes the (SM) weak couplings of the “up” type quarks with the “down”.
- It is unitary by construction, and can be described by four, experimentally measured parameters.

**The “Wolfenstein” parameterization**

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} = \begin{pmatrix}
1-\lambda^2/2 & \lambda & A\lambda^2(\rho - i\eta) \\
-\lambda & 1-\lambda^2/2 & A\lambda^2 \\
A\lambda^3(1-\rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + \ldots
\]

- $\eta$ is the parameter which characterizes the scale of CP violation in the SM.
\( V_{ub} \) and the Unitarity Triangle

We can draw a triangle in the imaginary plane based on the unitarity of this matrix.

\[
V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0
\]

- \( V_{ub} \), along with \( V_{td} \), are the most poorly measured elements.
- Experimental Goal: Measure all sides and angles of this triangle in order to look for inconsistencies in the SM.
The Exclusive $V_{ub}$ Measurement

In principle, given the branching fraction and form factor for a specific decay, $\bar{B}^0 \rightarrow \pi^+ l^- \nu$, one can extract $V_{ub}$ from the following expression:

$$\frac{d\Gamma}{dq^2} = \frac{G^2}{24\pi^3} |V_{ub}|^2 p_{\pi^3} |f(q^2)|^2$$

$f$ is the form factor and $q^2$ is the invariant mass of the virtual W.

The biggest errors in determining $V_{ub}$ exclusively are in the theoretical uncertainties of the form factor.
More on Form Factors

• Form factors parameterize the QCD interactions between the quarks in the decay.
• Those of the “heavy to light” quark decays (b->u,d and c-> u,d) must be calculated nonperturbatively and are poorly understood.
Exclusive $V_{ub}$ in the Past and Present

This has been done before at CLEO…

$$V_{ub} = (3.25 \pm 0.14^{+0.21}_{-0.29} \pm 0.55) \times 10^{-3}$$

(Average of previous exclusive results from hep-ex/9905056)

8-10% experimental  17% theoretical

We are currently attempting to obtain branching fractions for the following modes: $B \rightarrow \pi, \rho, \eta, \omega, \nu$.

Improvements with this analysis:

• Greater statistics - 3X the luminosity of the previous analysis.
• We expect to obtain better $q^2$ distributions, and therefore have a much greater sensitivity to theoretical models.
The Basic Analysis Technique

The idea is simple…

• Sum up the energy and momentum of all the particles in an event and attribute what is missing to the neutrino.

Some definitions: \( \bar{p}_v = - \sum_{i \text{ good tracks}} p_i \)

Reconstruct the B using this ν plus the candidate lepton and hadron tracks.

…but the requirements for good neutrino reconstruction make this analysis difficult.
The Basic Analysis Technique

continued...

- Simultaneously fit the $M_B$ and $\Delta E$ distributions to extract a yield.

Some more definitions:

\[
\Delta E = (E_\nu + E_\ell + E_h) - E_{\text{beam}}
\]

\[
M_B = \sqrt{E_{\text{beam}}^2 - \left| \vec{p}_\nu + \vec{p}_\ell + \vec{p}_h \right|^2}
\]
Extracting $V_{ub}$

- The last step is to use various theoretically determined form factors to extract a value of $V_{ub}$.
- Quark Models, Dispersion Relations, Light Cone Sum Rules, and Lattice QCD will all be used.
Now switching to a different, but related analysis…

- The decay $D^0 \rightarrow \pi l\nu$ is also a “heavy to light” decay.

\[
\begin{array}{cccc}
\bar{u} & \overline{u} & \bar{d} & \overline{d} \\
c & d & b & u \\
W^+ & \nu & W^- & \nu \\
l^+ & l^- & & \\
\end{array}
\]

- Because the CKM element involved in this decay is already well measured via deep inelastic neutrino scattering, a measurement of this branching fraction could provide better understanding of “heavy to light” form factors.

\[
\frac{d\Gamma}{dq^2} = \left(\frac{G^2}{2\pi^3}\right) |V_{cd}|^2 p_\pi^3 |f(q^2)|^2
\]
Past Measurements and New Expectations

We have some knowledge of this branching fraction through previous measurements of the ratio \( \frac{D^0 \rightarrow \pi l \nu}{D^0 \rightarrow Kl \nu} \).

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Ratio</th>
<th>Statistical Error</th>
<th>Systmatic Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mark III</td>
<td>0.115</td>
<td>+0.073/-0.037</td>
<td>0.018</td>
</tr>
<tr>
<td>CLEO II</td>
<td>0.170</td>
<td>0.054</td>
<td>0.028</td>
</tr>
<tr>
<td>CLEO II and II.V</td>
<td>0.103</td>
<td>0.039</td>
<td>0.013</td>
</tr>
<tr>
<td>E687</td>
<td>0.101</td>
<td>0.020</td>
<td>0.003</td>
</tr>
<tr>
<td>CLEO III</td>
<td>??</td>
<td>~0.012</td>
<td>??</td>
</tr>
</tbody>
</table>

CLEO hopes to make a new measurement of this ratio with data from our new (CLEO III) detector.
The Analysis Technique

• “Tag” the D⁰ with the decay $D^{*+} \rightarrow \pi_s + D⁰ \rightarrow \pi (K) l \nu$

• Then we construct a mass difference.

$$\Delta M = M_{\pi_{slow} \pi(K) l \nu} - M_{\pi(K) l \nu}$$

We expect improvements with the addition of neutrino reconstruction...
The CLEO III Analysis of $D^0 \to \pi l\nu$

...but there’s room for an even bigger improvement!

- Previously, the decay $D^0 \to K^- l^+ \nu$ contributed a large background.
- We hope to improve greatly on the old CLEO analysis because we can now distinguish pions from kaons well with our new particle ID detector.

(CLEO II Result)
A new feature in CLEO!

- The Rich detector is a ring imaging Cherenkov detector.
- It covers 83% of the solid angle in CLEO III.
- We expect 90% efficiency in the RICH for both pion and kaon detection with $p>0.7\text{GeV}$. 

Data: $D \rightarrow K\pi$ Mass Peak 

Plot by Gocha Tatishvili
In Summary

*We are expecting results soon on two interesting analyses being performed at CLEO:*

- $B \rightarrow \pi, \rho, \omega, \eta/\nu$
  - A CLEO II/II.V analysis from which we hope to extract one of the most current and precise measurements of $V_{ub}$.
- $D^0 \rightarrow \pi \ l\nu$
  - A CLEO III analysis!
  - Will help provide understanding of “heavy to light” form factors which are a major source of theoretical uncertainty in determining $V_{ub}$. 
For the Future…

CLEO has been making contributions to B physics for over 20 years, but our time is coming to an end…

So what is next?

• In the next decade, we will be changing our focus from b-physics to charm-physics.
• $\pi \ell \nu$ is among the modes we expect to make a precision measurement of with a less than 2% error on the branching fraction.
• Much promise lies ahead in understanding these non-perturbative form factors and extracting a precise value of $V_{ub}$
Why an Exclusive Measurement?

The advantage of an exclusive $B \rightarrow u l \nu$ measurement:

- $B \rightarrow c l \nu$ contributes large backgrounds, making the inclusive measurement of $B \rightarrow u l \nu$ difficult for all but the very endpoint of the lepton momentum spectrum.
- Ultimately, tools such as lattice QCD will give us very precise model independent ways to measure $V_{ub}$ exclusively.
- An exclusive measurement would serve as a much needed cross check for the inclusive measurement.
The Cornell Electron Storage Ring

- Located at Wilson Synchrotron Lab in Ithaca NY
- CESR is a *symmetric* e+e- collider with a CM energy of 10.56 GeV.
- CLEO and CESR have been producing results in B physics for over 20 years.
Neutrino Reconstruction Tools

…but the requirements for good neutrino reconstruction make this analysis difficult.

Trackman

• Ensures that we have good tracking by eliminating extra tracks introduced by pattern recognition artifacts.

Splitoff

• Since we only take either a good track or a good shower, scattering in the calorimeter can mimic extra neutral particles which are not real.
The CLEO II/II.V Detector

- Symmetric e+e- collider.
- Good Hermiticity - 93% of the solid angle is covered in tracking, and 98% in calorimetry. This is necessary for good neutrino reconstruction.
- We operate at the $\Upsilon(4S)$ resonance.
Possible Improvements to the Analysis Technique

We are hoping to improve on the old CLEO analysis technique.

- Previously there was no attempt to reconstruct neutrinos.
- We are investigating the potential for improvement with neutrino reconstruction.

Fixing $M_D$ gives an ellipse of possible neutrino momenta, for a given $P_{\text{had},\text{lep}}$. 

Mass Difference

$\pi$ and $K \ell \nu$ MC

$w/\nu$ recon.

$w/o\nu$ recon.

0.12 0.16 0.20

GeV

2/16/2002 Lauren Hsu - Cornell University, CLEO Collaboration
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Testing the Standard Model

*CP violation is an area in which we can test for “new physics”*

- Our goal is to check whether the rate of CP violation predicted by the Standard Model matches what we see in nature.

\[ b \xrightarrow{\bar{u}, \bar{c}, \bar{t}} \bar{b} \]

\[ \bar{b} \xrightarrow{u, c, t} b \]

- Inconsistencies would signify new physics.
V_{ub} and the Unitarity Triangle

• In this parameterization, $V_{ub}$ and $V_{td}$ are the only terms which can produce CP violation.

$$
\begin{vmatrix}
1-\frac{\lambda^2}{2} & \lambda & A\lambda^2(\rho-i\eta) \\
-\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1
\end{vmatrix}
$$

The sizes of the four parameters are as follows: $A \approx 1, \lambda \approx 0.22$.